Digital Mapping of Buried Pipelines with a Dual Array System

R&D Project jointly funded by

U.S. DOT

ConEdison

Witten Technologies Inc.

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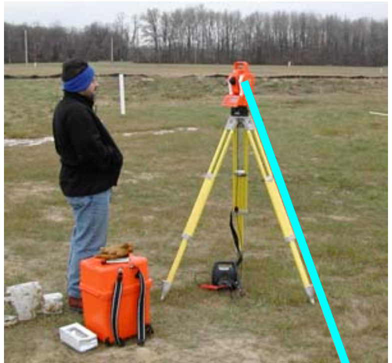
Dual Array Project

- Goal is to develop a non-invasive system for detecting and mapping buried steel and plastic pipelines efficiently over large areas

- Technology will combine surface measurements from radar and electromagnetic induction sensors with precise positioning and advanced image processing to create digital maps

Dual Array System January 2004



Accurate Positioning System
Self-tracking Laser Theodolite

Radar Array

Array of Induction Receivers (AIR)

+ GP*i*R Software

+ AIR Software

+ Clamp-on and On-Board Transmitters

Markets and Applications

- Utility Network Mapping and Construction Planning
- Subsurface Utility Engineering
- Facility Management
- Environmental Applications
  - Leak detection in pipelines
  - Unexploded ordnance (UxO)
  - Brownfield clean-up
- Other possible applications
  - Crime Scene Investigations
  - Monitoring
  - Bridge Deck / Concrete Evaluation / Highway Inspection

Outline

- Ground Penetrating *imaging* Radar
  - System overview
  - Example project
- Array of Electromagnetic Induction Receivers
  - System overview
  - Field Tests
- Dual Array Field Test
  - RWA survey in Hamden, CT
- Summary
- Outlook for 2004 and beyond

Ground Penetrating *imaging* Radar (GP*i*R)

System Overview

Ground-Penetrating Imaging Radar
(Radar Tomography)

Joint development of

Witten Technologies, Malå Geoscience, ConEdison

Schlumberger, EPRI and GTI

Ground Penetrating imaging Radar (GP*i*R)

GP*i*R: A GPR survey or system that combines efficient radar surveying with precise positioning control and advanced signal processing allowing the creation *high-resolution* 3D radar images of the subsurface on a *large-scale*.

Meaning:

"*precise positioning*" = centimeters

"*large-scale*" = surveys covering thousands of square meters

"*high-resolution*" = resolution of centimeters

CART Imaging System

Computer-Assisted Radar Tomography

Total daily coverage:
- 40,000 – 80,000 sqft

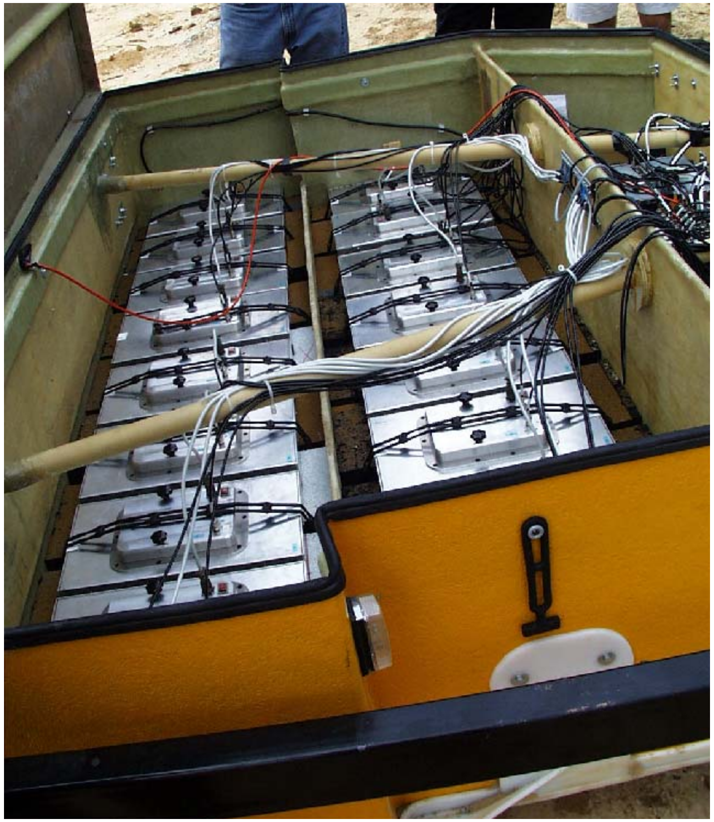
Spatial resolution:
- ~ 5” channel or cross-line spacing
- ~ 4” trace or in-line spacing

Maximum Driving Speed:
- 3 mi/hr

Radar component of CART Imaging System is manufactured by Malå Geoscience

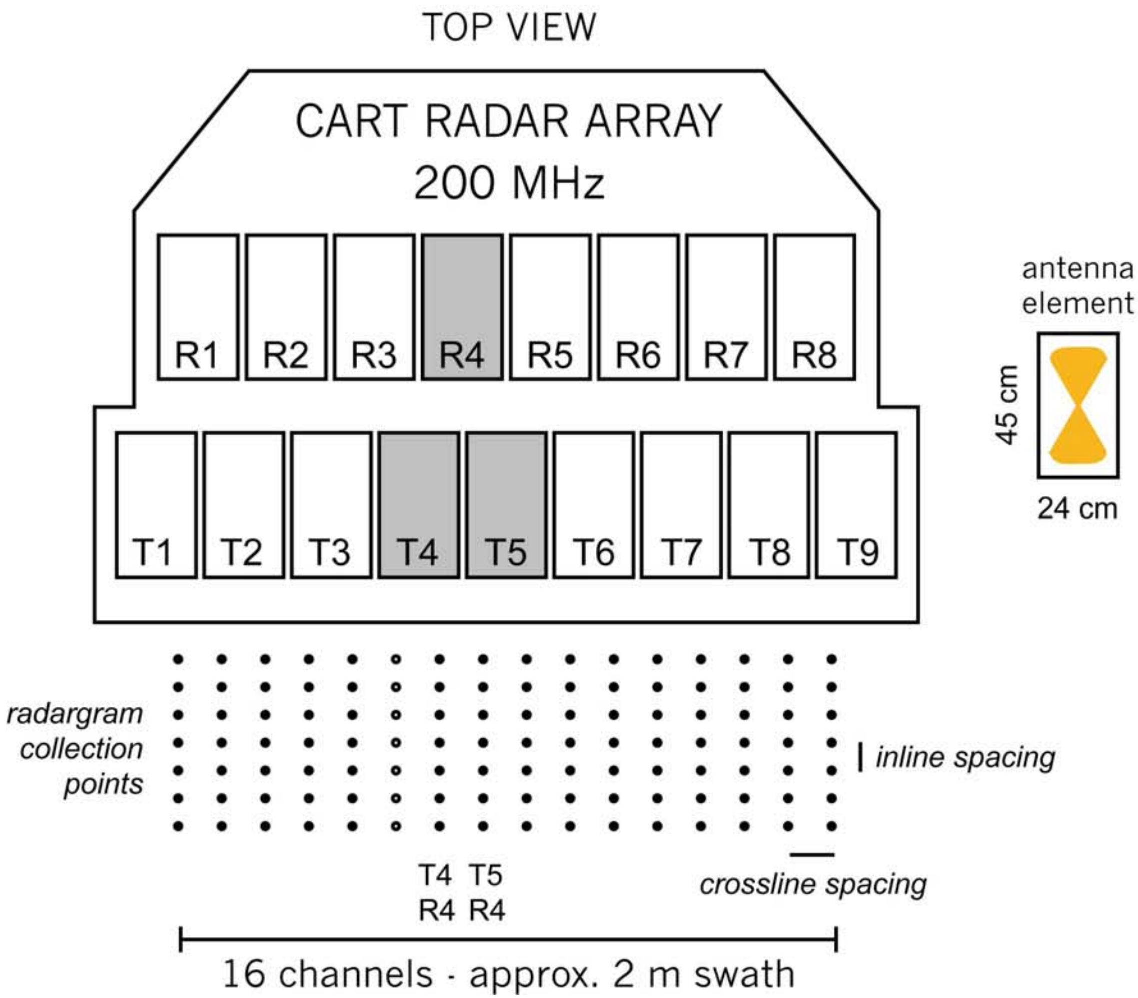
CART Imaging System

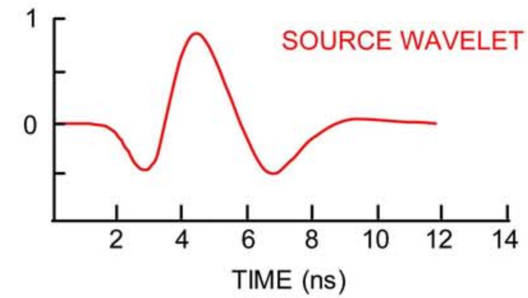
Computer-Assisted Radar Tomography

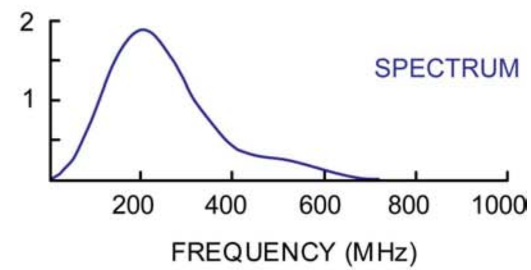


- 17 ultra-wideband GPR antennas
- 9 transmitters and 8 receivers
- 200 MHz peak frequency
- 50 to 400 MHz bandwidth

CART Imaging System (Schematic)



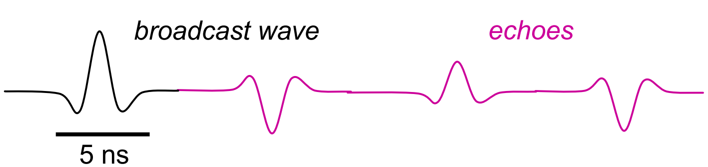


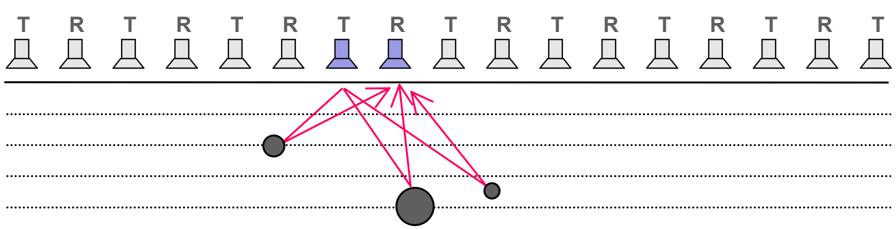


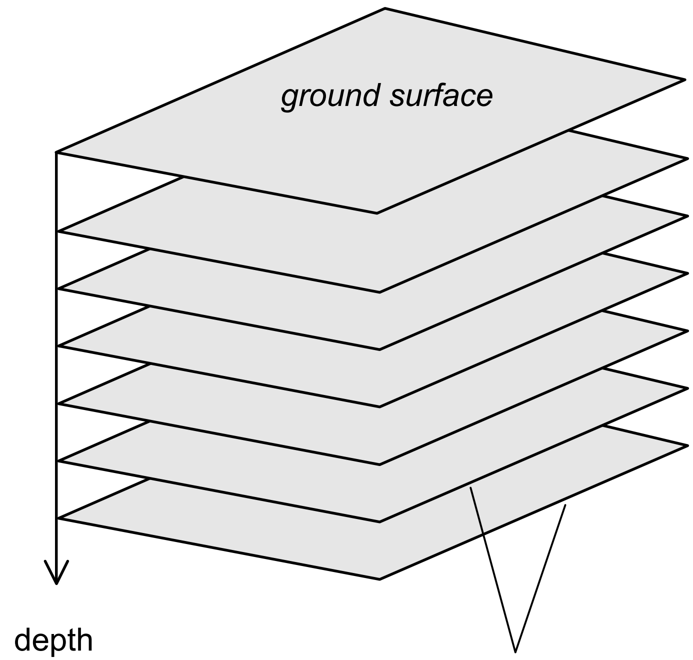
Radar Tomography

An ultra-wideband radar array riding close to the ground can make a 3D underground image by focusing to create image "slices" at different depths.

16-channel down-looking ultra-wideband radar array







Synthetic-aperture focusing creates image "slices" at different depths below ground to make a 3D image

CART Imaging System (Positioning)

- Precise geometry control provided by a self-tracking laser theodolite locking on to a 360 degree prism
- Accurate positioning (~.1 in) over distances of 1500 ft
- The laser theodolite is also used to map surface features to provide a local reference map for the final 3D radar images of the underground

Technology Advances Incorporated

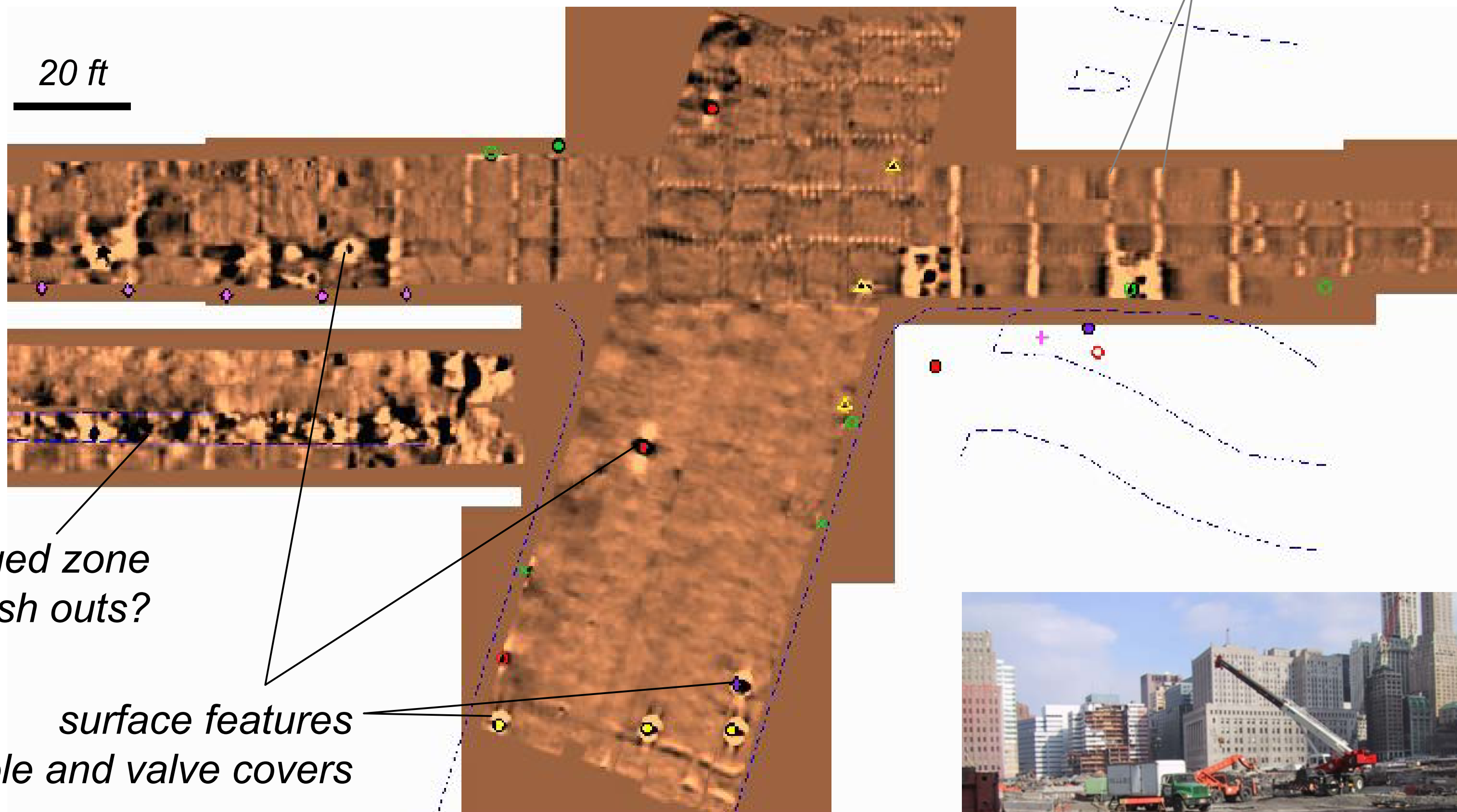
- Ultra-wideband GPR array (200 MHz center frequency)
  - 16-channel bi-static array allows continuous coverage of a 6-ft swath with 5 in. channel or cross-line spacing
  - 100 kHz data collection rate allows 4 in. sampling in profile direction (in-line spacing) while moving at speeds up to 3 mi/hr
- Accurate positioning (~.1 in) over distances of 1500 ft
  - Laser theodolite (LIDAR)
  - Can be tied to local features (curb or building lines) and to global coordinates using GPS and standard surveying techniques
- Software that merges data into a seamless image
- Software that allows us to deliver utility maps in engineering type maps (CAD or GIS)

Technical Specifications

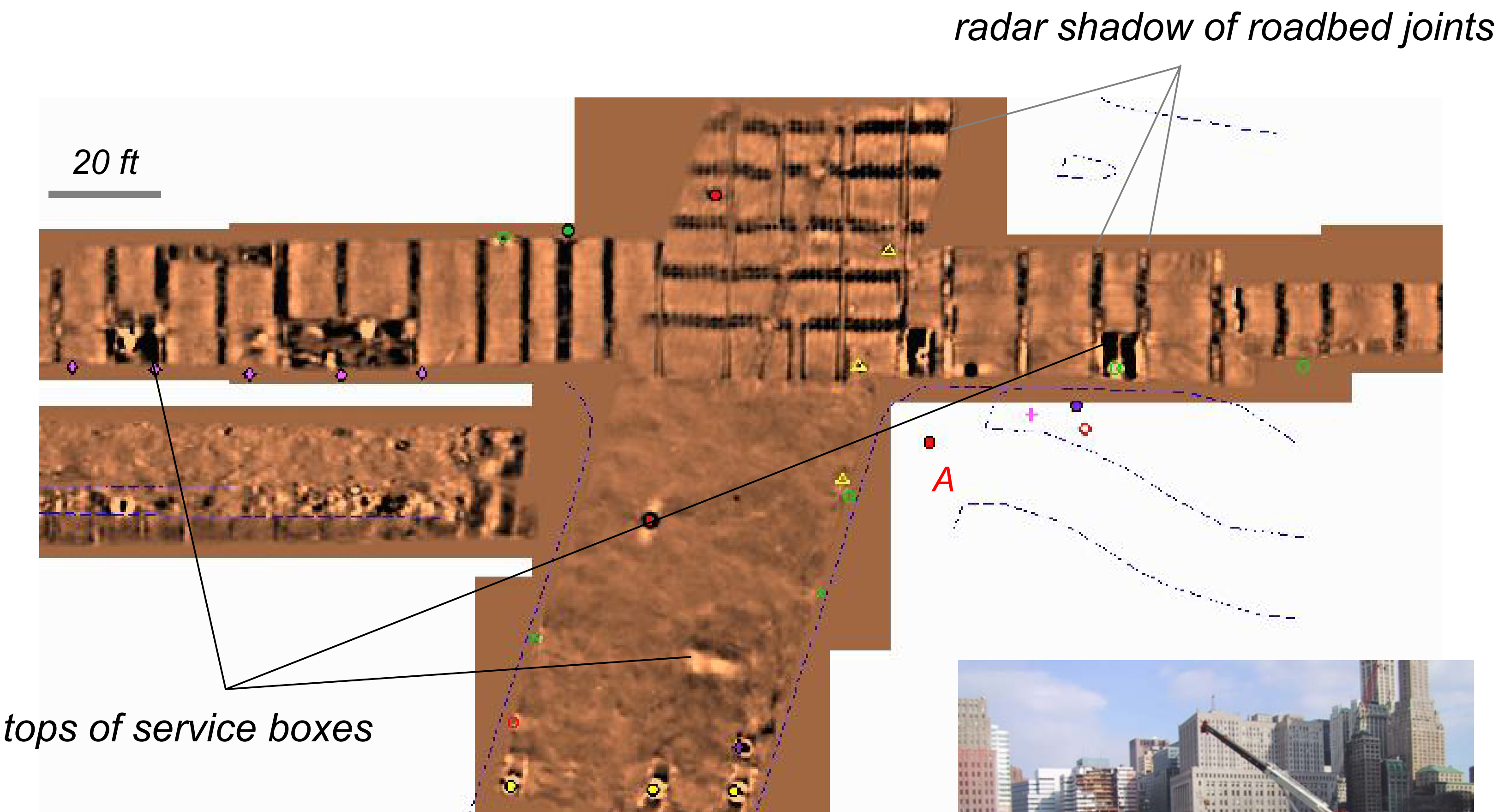
- Depth of penetration is 4 to 6 ft in most sandy-clay soils (8 to 12 ft in sandy soils)
- Depth accuracy is about 5% (ie, +/- 3 inches over 5 ft)
- Horizontal accuracy is about 1% from mapped surface features such as manhole covers or curb lines
- Resolution of subsurface objects is about 3 to 4 inches
  - Objects as small as 1-inch can be seen at shallow depths
  - Resolution degrades with depth at rate of about 1 inch/ft

Ground Penetrating *imaging* Radar (GP*i*R)

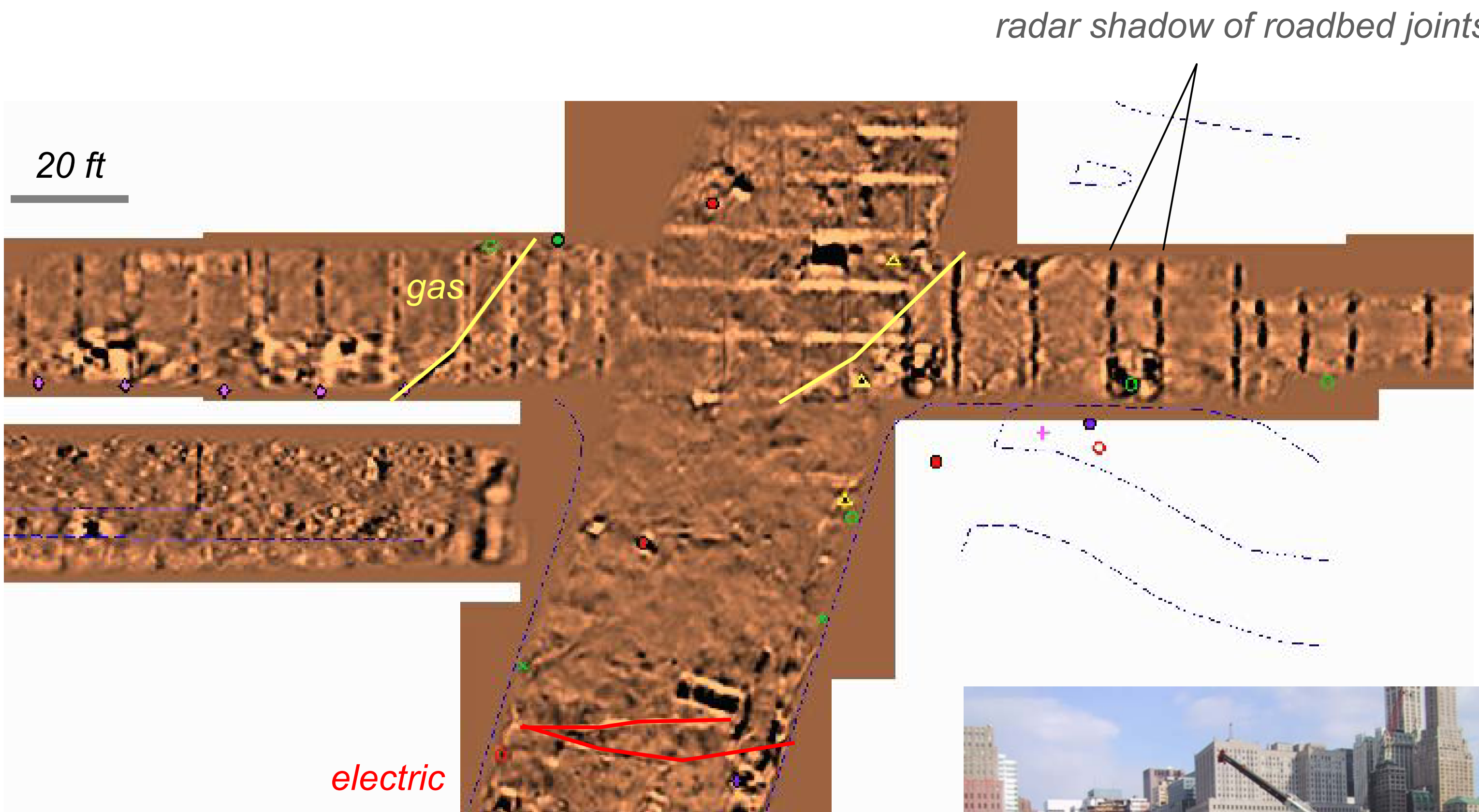
Example from the Lower Manhattan Radar Project



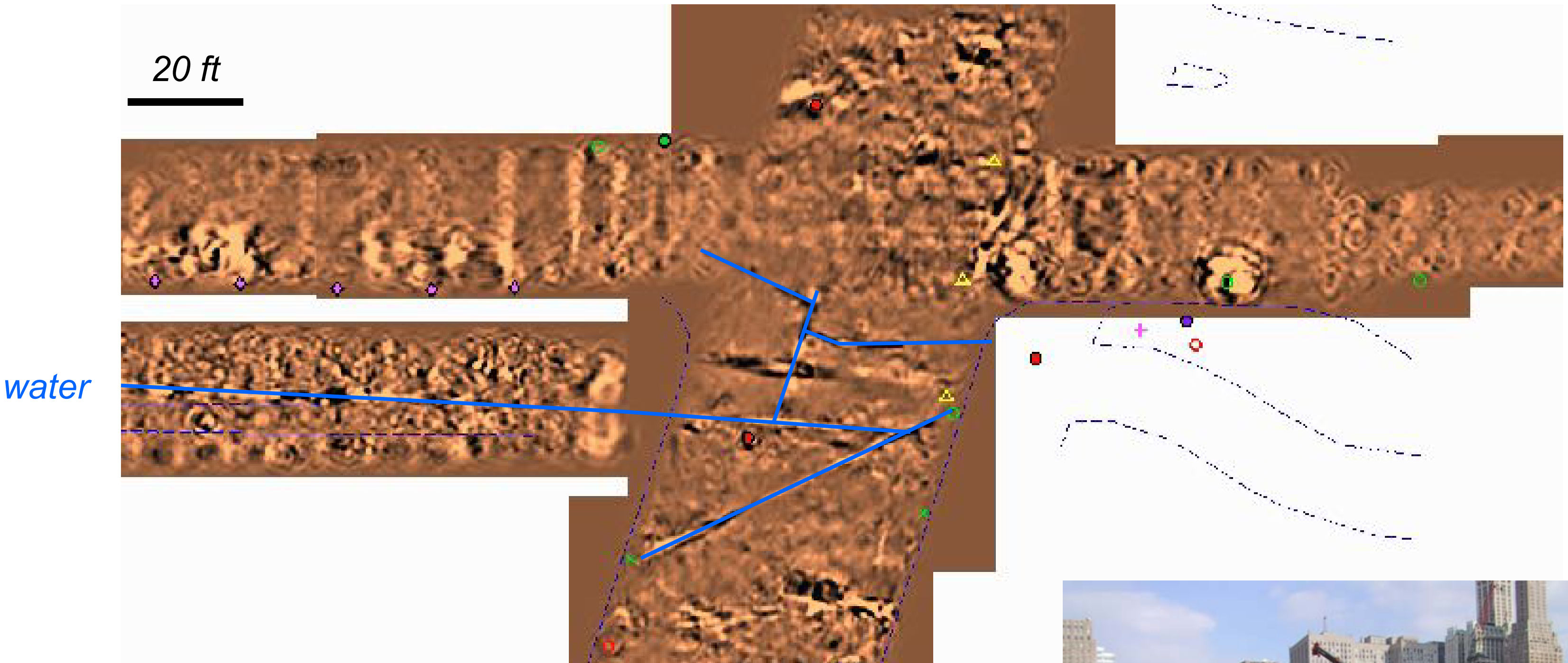
RADAR IMAGE
2 inches below street level



RADAR IMAGE
12 inches below street level



RADAR IMAGE
24 inches below street level



RADAR IMAGE
42 inches below street level

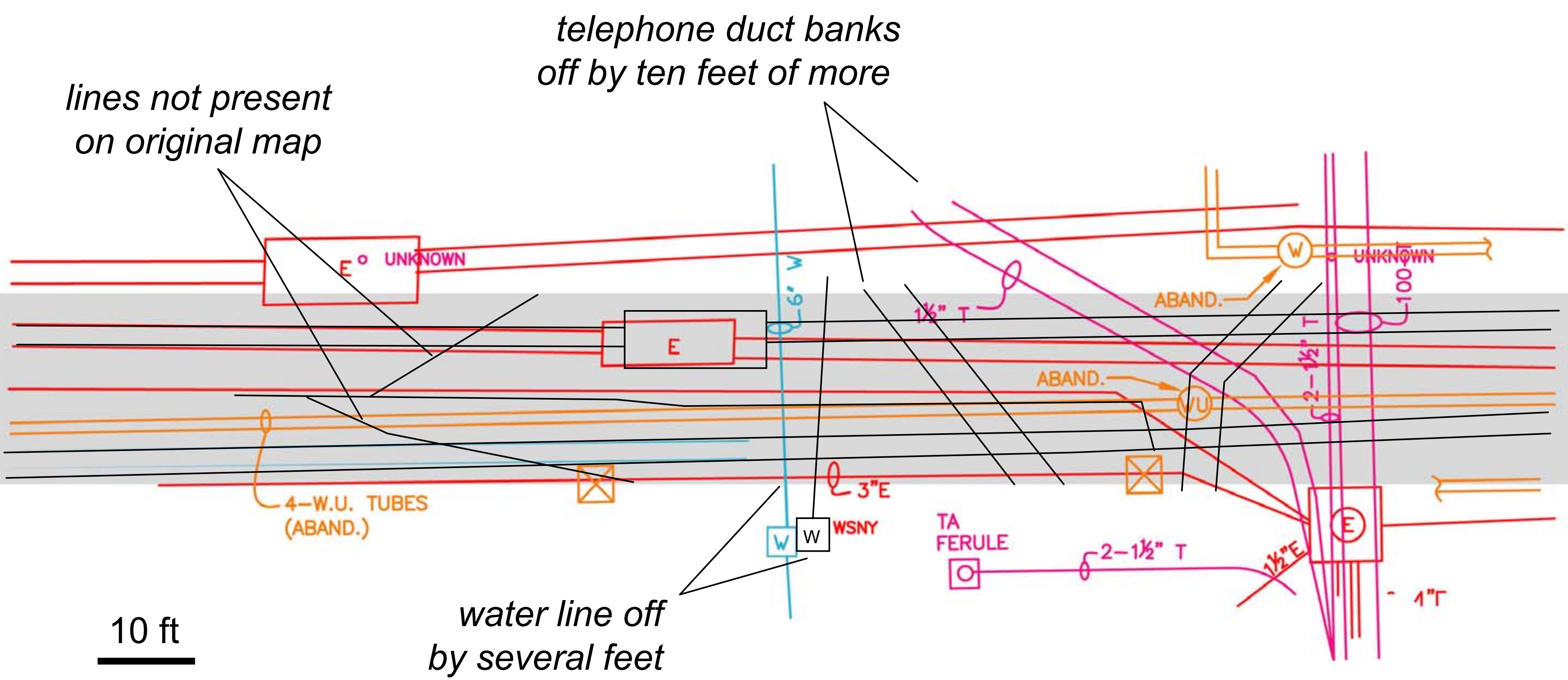
Summary

Lower Manhattan Underground Radar Project

- Covered 320,000 sq ft in about one month (15 nights)
- Produced a continuous 3D image below streets near ground zero with 5 in. by 4 in. horizontal pixel resolution and 1 in. depth resolution

- *Images helped (a little) with*
  - Locating existing structures (avoiding digging and accidents)
  - Finding clear lane for new installations
  - Creating integrated (corrected) infrastructure maps

Corrected Maps



Colored lines show utility locations according to available maps.

Black lines show actual locations (of selected utilities) determined by radar tomography.

Array of Induction Receivers (AIR)

System Overview

Array of Induction Receivers

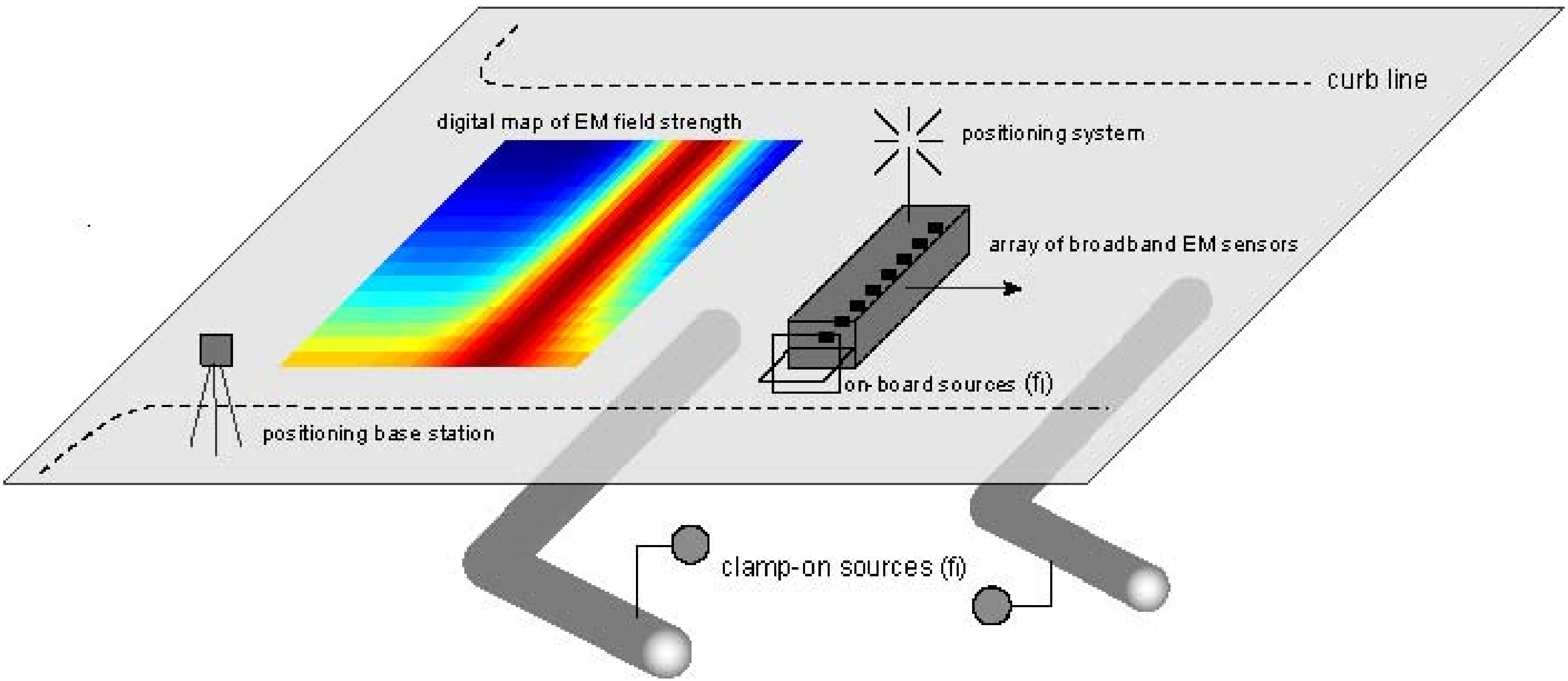
R&D Project jointly funded by

Witten Technologies, ConEdison and U.S. DOT

With contributions from Electromagnetic Instruments Inc.

and Regional Water Authority Connecticut

Array of Induction Receivers (AIR) System Principles



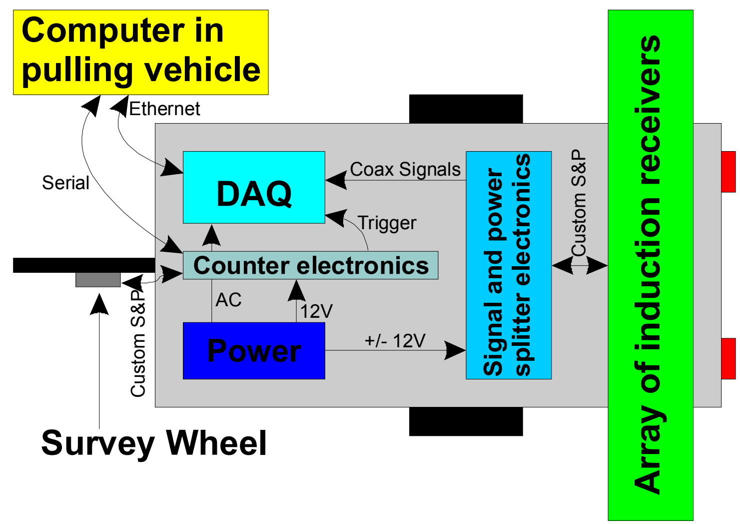
48-Channel AIR Prototype System

- Trailer based like pulled GP*i*R system
- Looking at first custom designed and manufactured prototype made from non-metallic fiberglass
- Sensor-shelf moves between acquisition and transport positions

Array of Induction Receivers

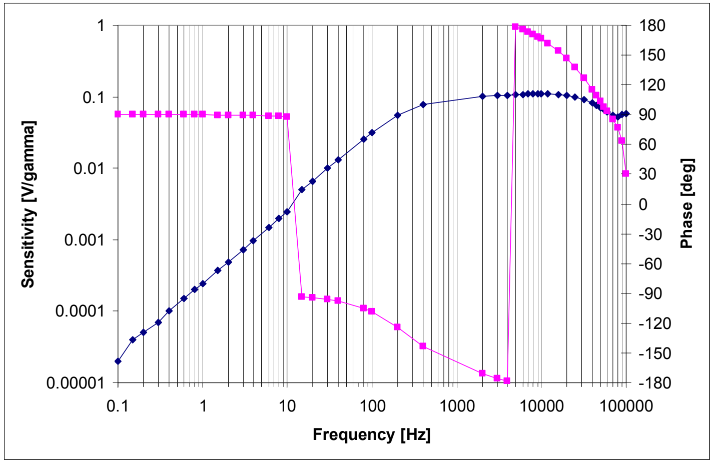
- 90 pocket *sensor-shelf*
- 16 coil pods
- 48 channels
- 8 feet swath

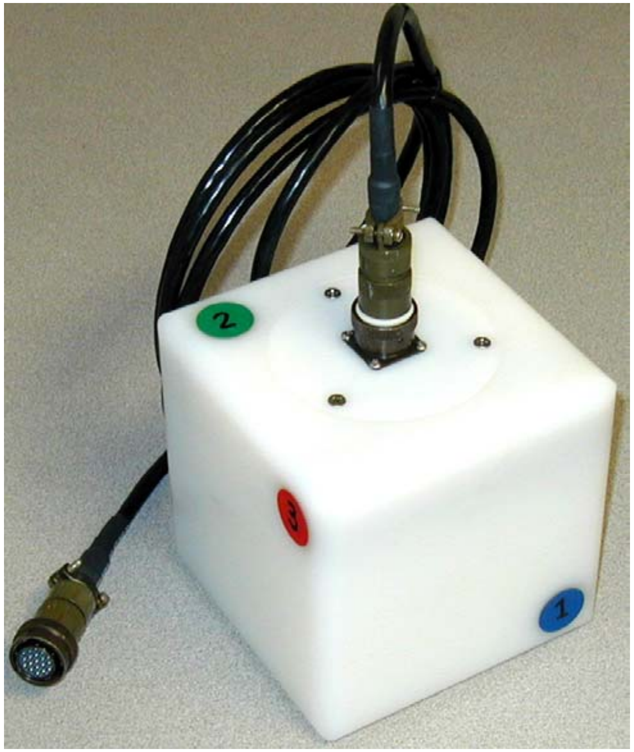
- Power and signal switchbox housed in main compartment
- Signals routed to DAQ system



AIR System Receivers

- Three component magnetic field sensors designed and built to specifications by EMI
- Length = 6” , Weight = 8 lbs, Power Input +/- 12V, Analog Output +/- 10V
- Coil flat response from 500 Hz to 50 kHz, above and below fall approximately linearly with frequency
- Noise level of coils (dep. on ADC Bits)
  - 0.0005 nT @ 1kHz
  - 0.0001 nT @ 10kHz



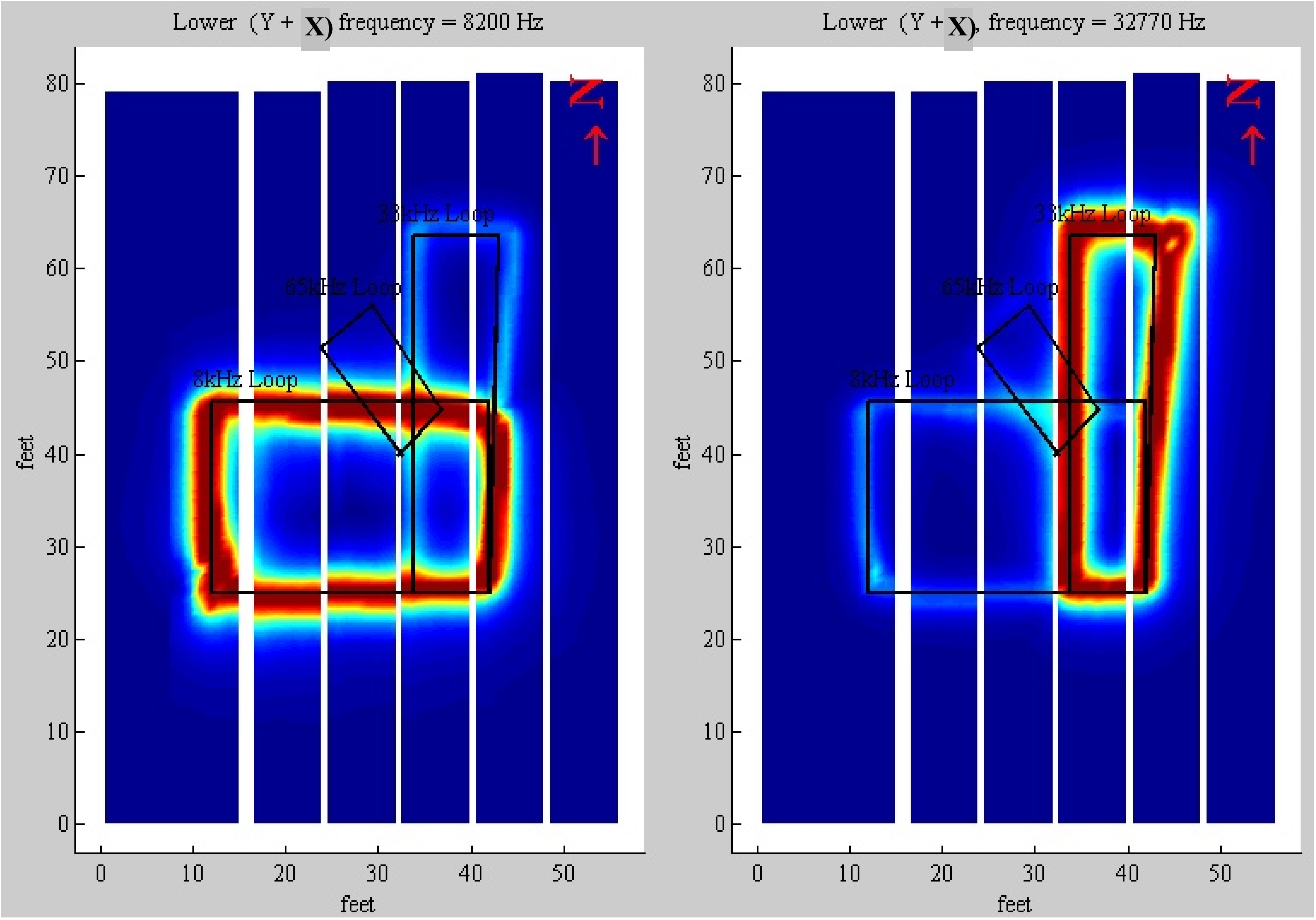


Array of Induction Receivers (AIR)

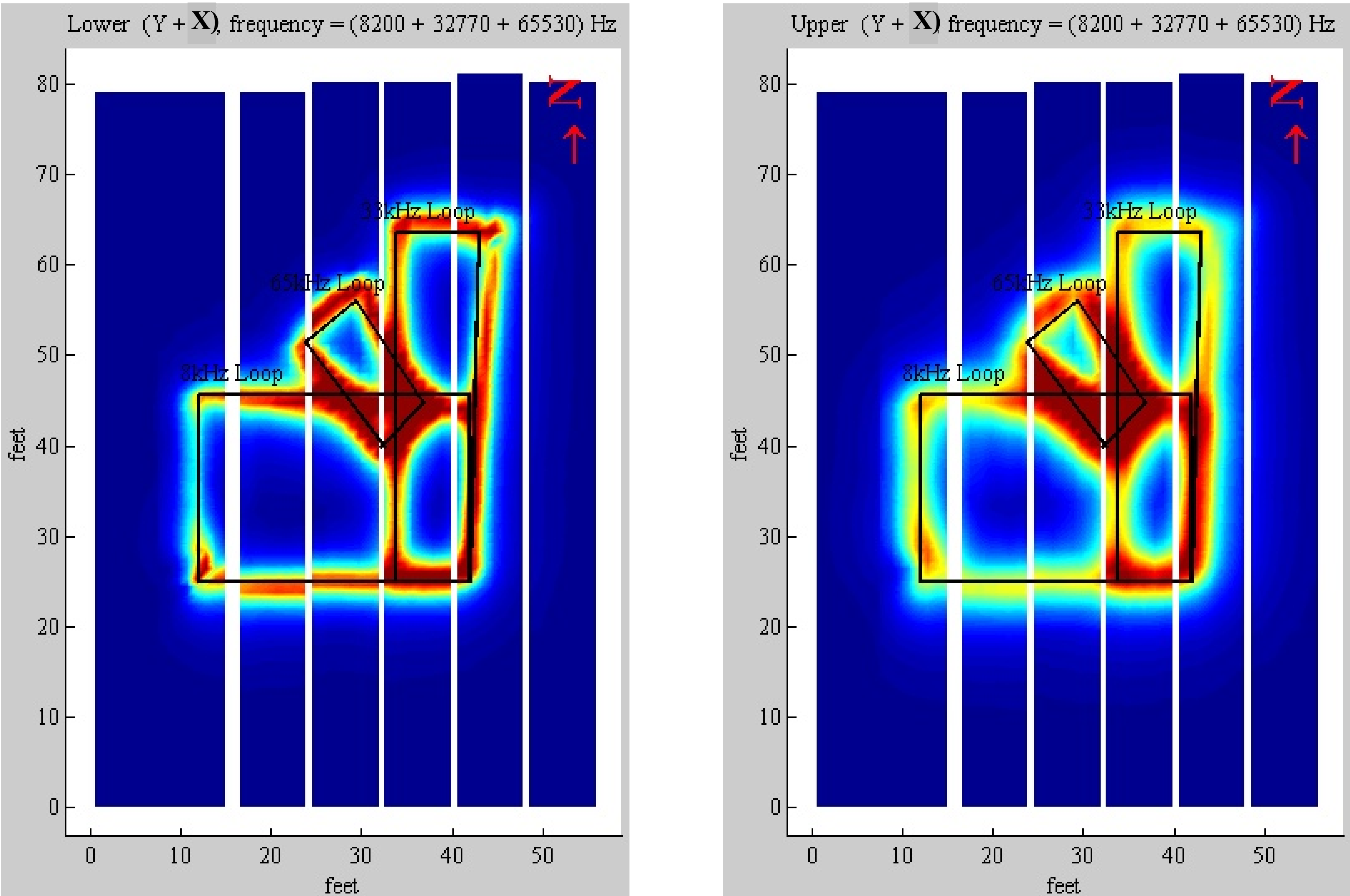
Field Test
Parking lot near Newton, MA

Parking Lot Survey, Newton, MA

Horizontal magnetic field component for 8 and 32 kHz



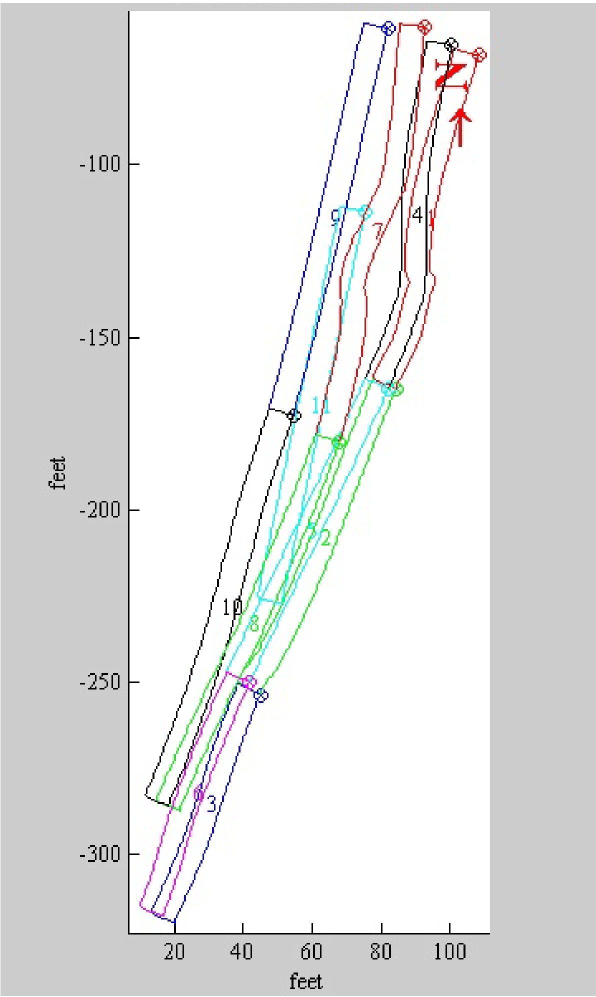
Horizontal magnetic field component for 3 frequencies



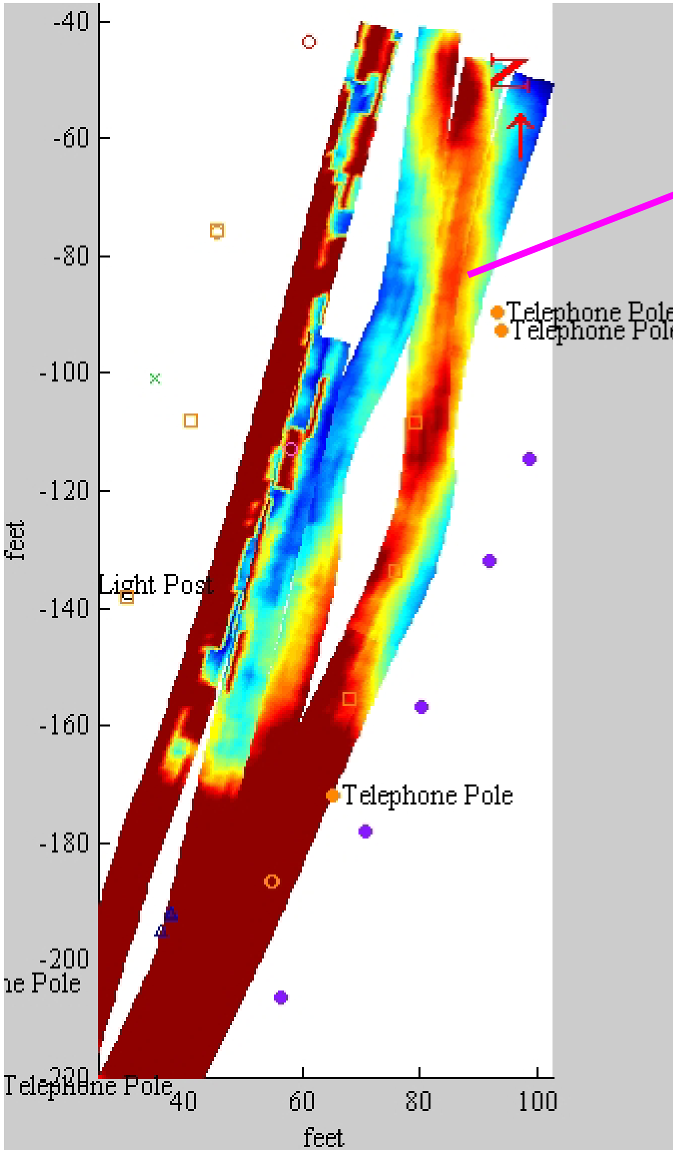
Dual Array Field Test

Regional Water Authority (RWA) site near Hamden, CT

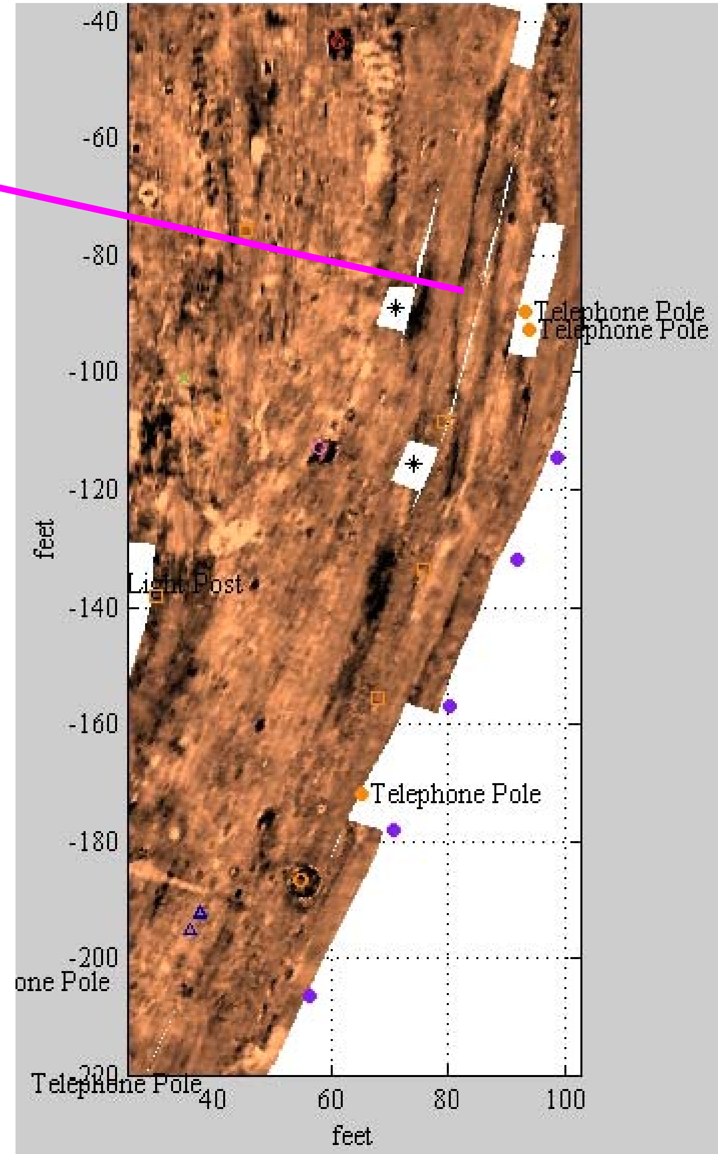
Survey Geometry



EM (8kHz) Image versus Radar (17" depth)

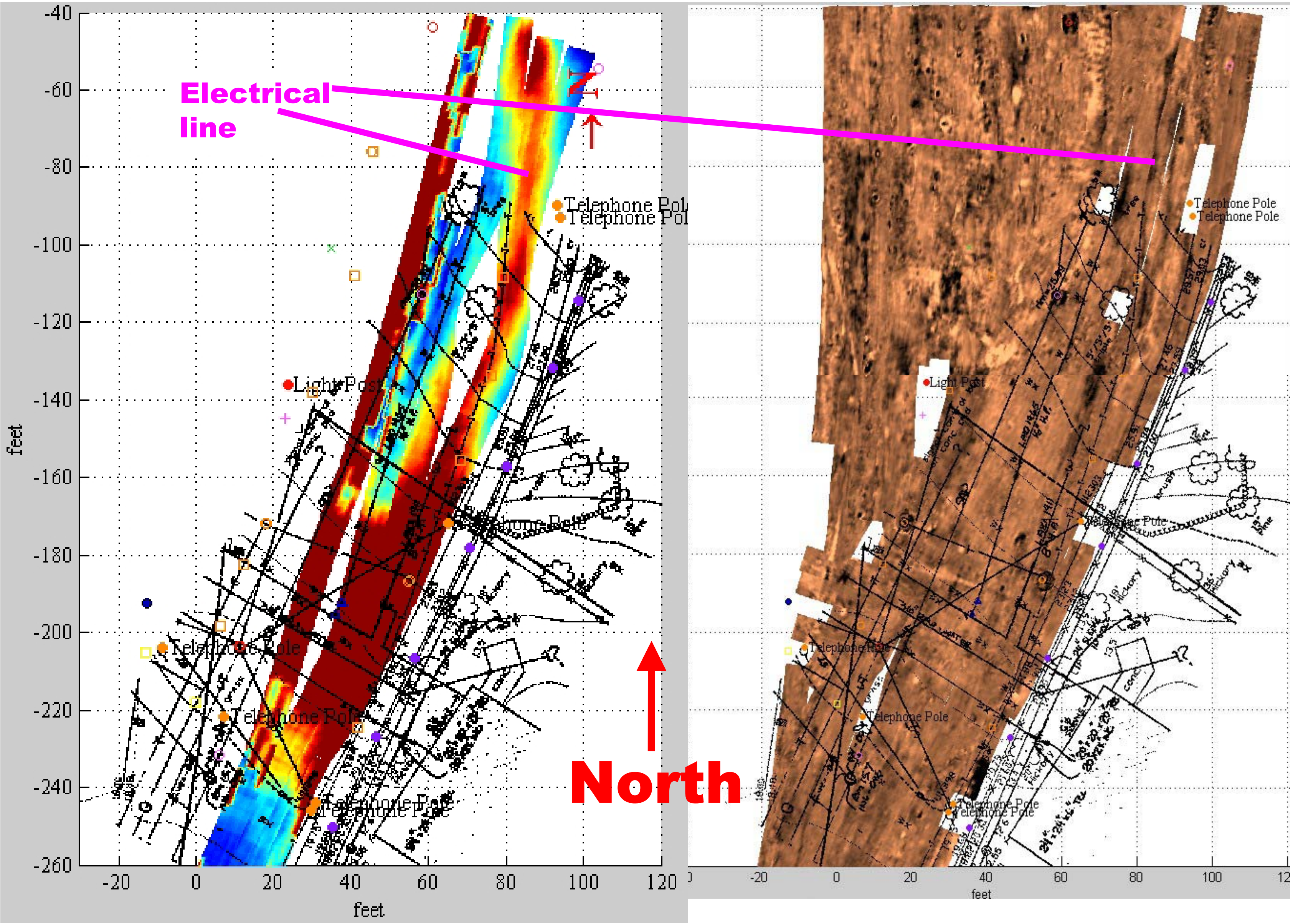


Electrical line

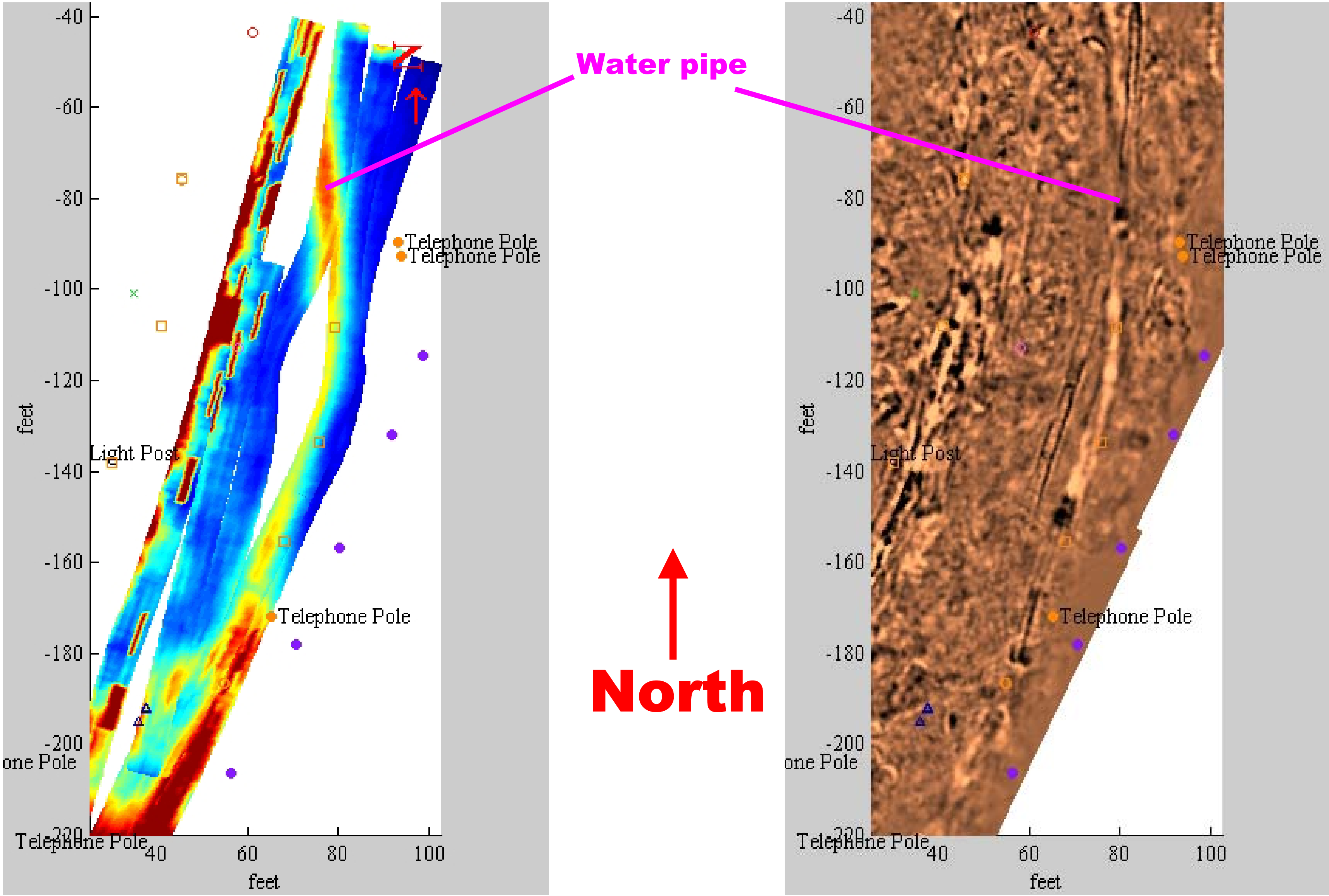


North

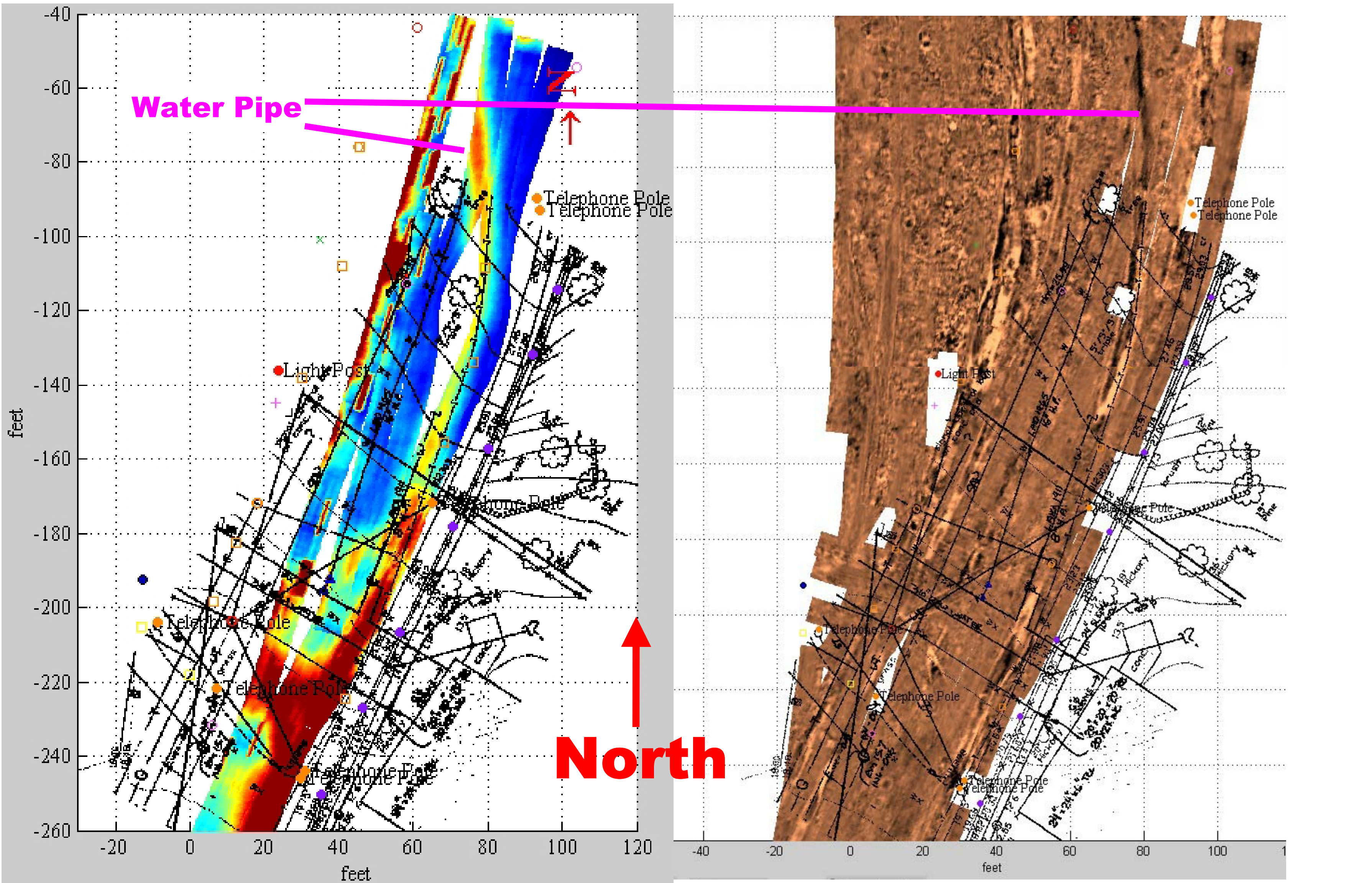
EM (8kHz) Image versus Radar (17” depth) + client map overlay



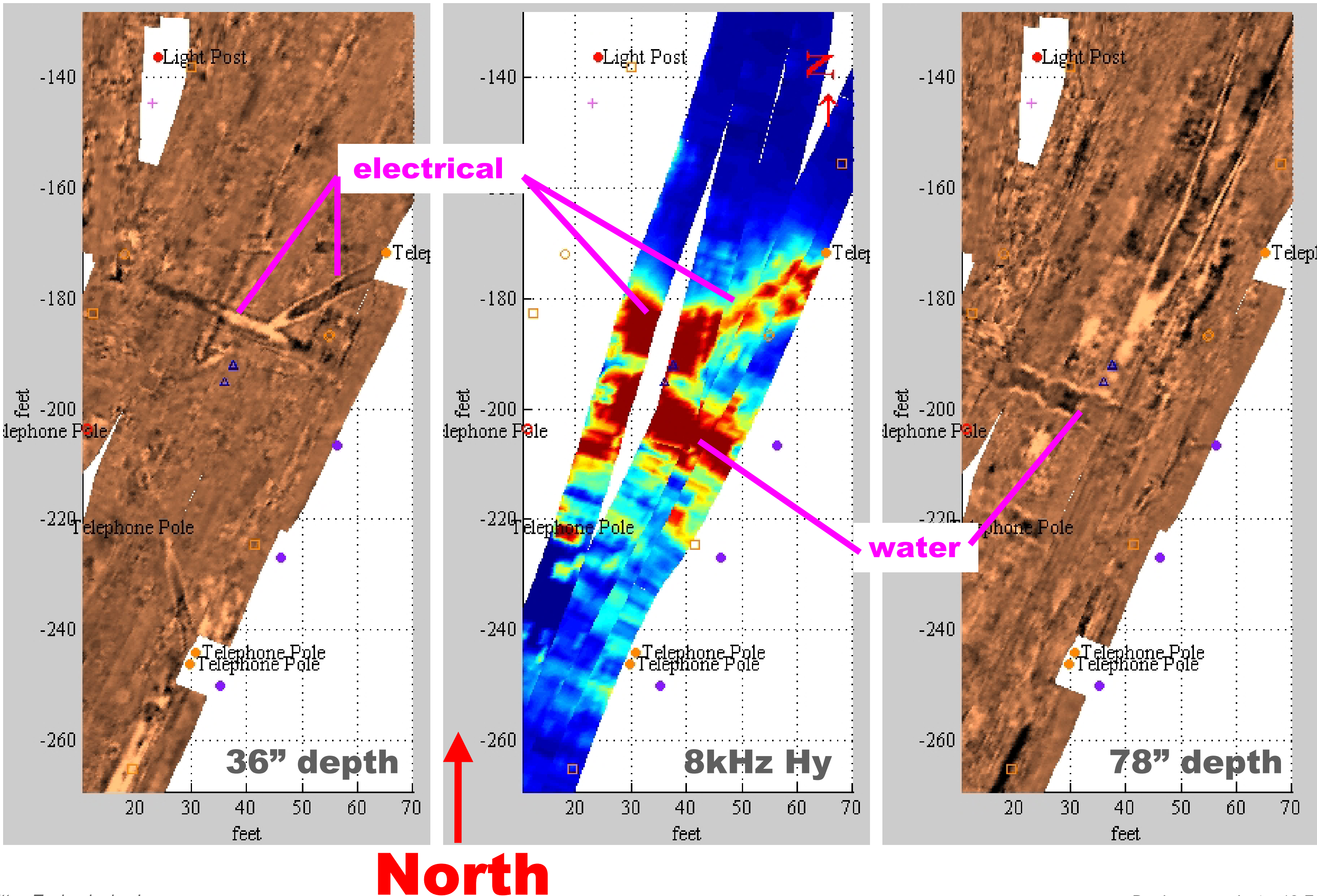
EM (32kHz) Image versus Radar (55” depth)



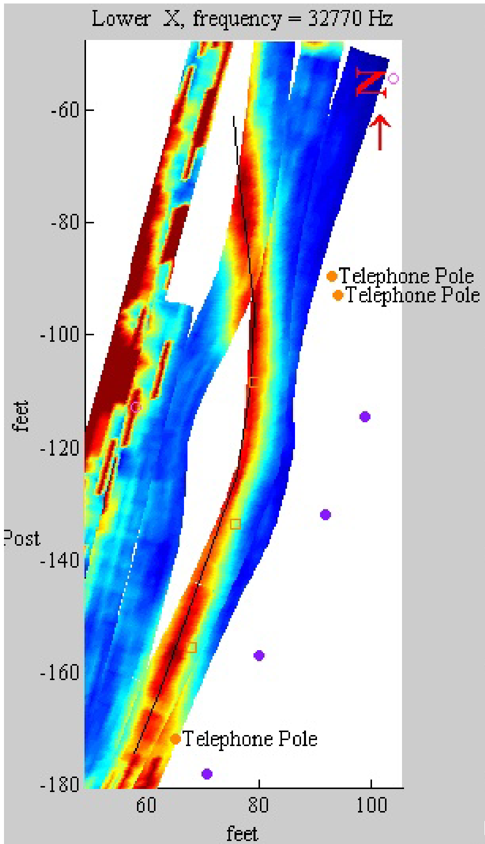
EM (32kHz) Image versus Radar (55” depth) + client map overlay

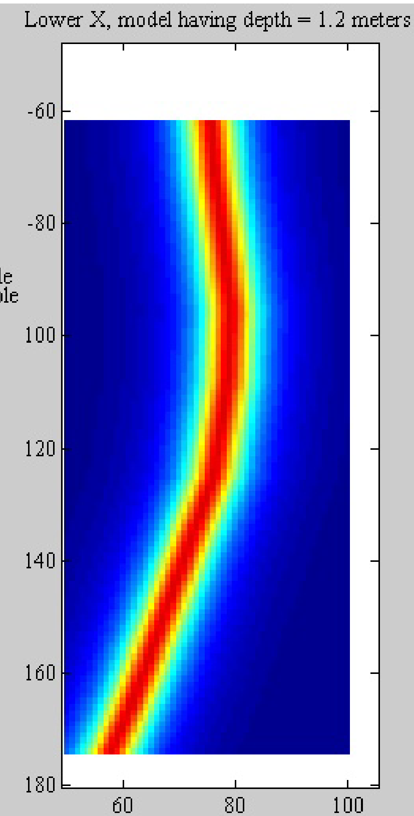


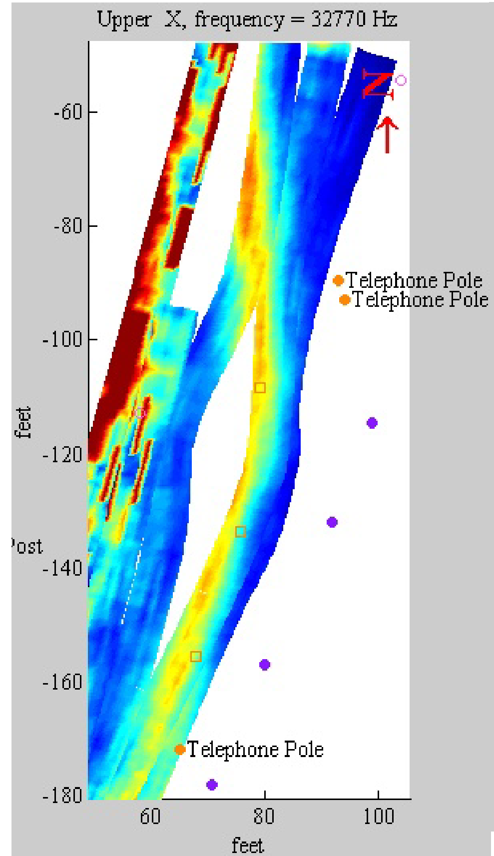
Radar (36” and 78” depth) vs. EM (8kHz) Image

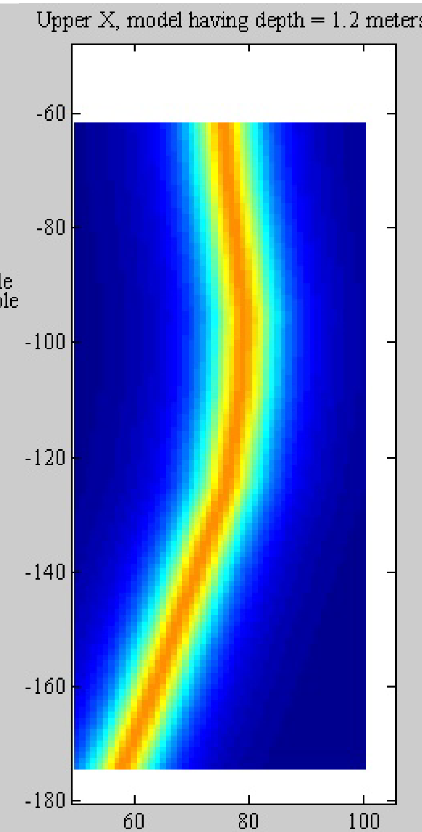


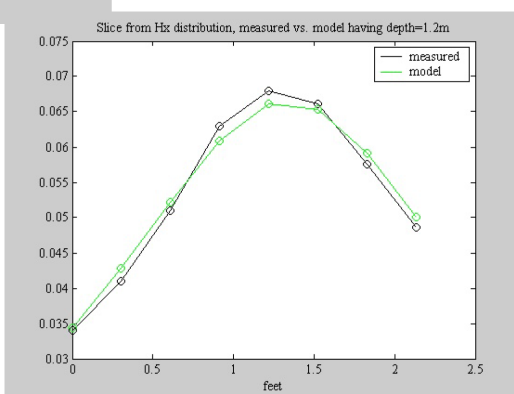
Model vs Field Data Comparison











Issues Encountered

- Picked up strong 60 Hz and Harmonics from overhead power lines and above ground switch boxes
  - Add high-pass filter to sensors before preamp to reduce this type of interference
- Currents clamped-on to one pipe pick return path through different pipe, putting signal on more than one pipe
  - Will be sorted out through numerical modeling/inversion

Modeling and Inversion

Parametric Inversion

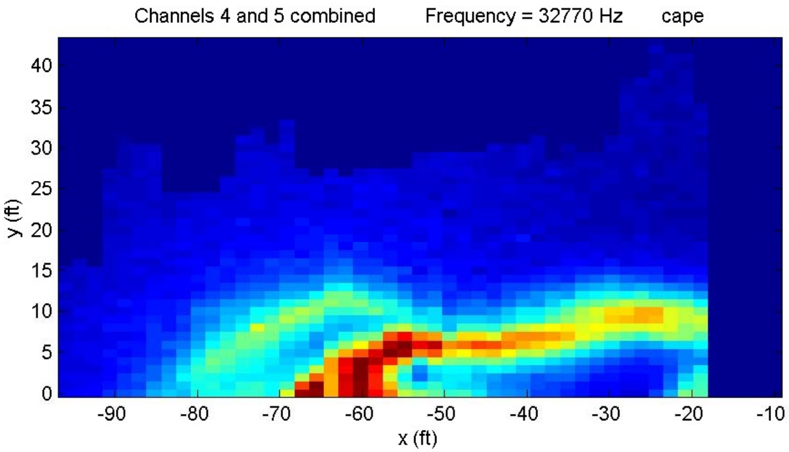
To estimate positions of the buried pipes, inversion software fits the measured digital maps of the vector magnetic field (at each frequency) with a parametric model of currents flowing along a network of buried pipelines. The current flowing along each pipeline is represented by an idealized current filament consisting of one or more straight-line segments. To represent possible leakage of current from the pipe into the surrounding soil, the amplitude of the current flowing along each segment is allowed to vary linearly between its values at the segment's nodes (endpoints). Different pipelines can intersect at the nodes; continuity (conservation) of the current is enforced at each node.

The user specifies an initial model, which consists of a number of underground pipes with a specified number of segments and intersections and an (arbitrary) initial guess for the amplitude of the current flowing in each pipeline.

The software then iteratively determines the 3D positions of the line segments and the amplitudes of the currents at the nodes by minimizing a cost function that measures the difference between measured and modeled magnetic fields. The number of pipe or segments in the model can be adjusted at any time during the inversion to achieve a better fit with the measurements or to simplify the model.

This inversion model is obviously geared to mapping networks of metal pipelines. Provided that current flows mainly along the (conducting) pipes, ambiguity in the final results will usually be minimal because of the redundancy provided by multiple transmitters at different frequencies and by multiple receiver positions (including receivers at different heights and coil orientations).

Cape Cod Survey

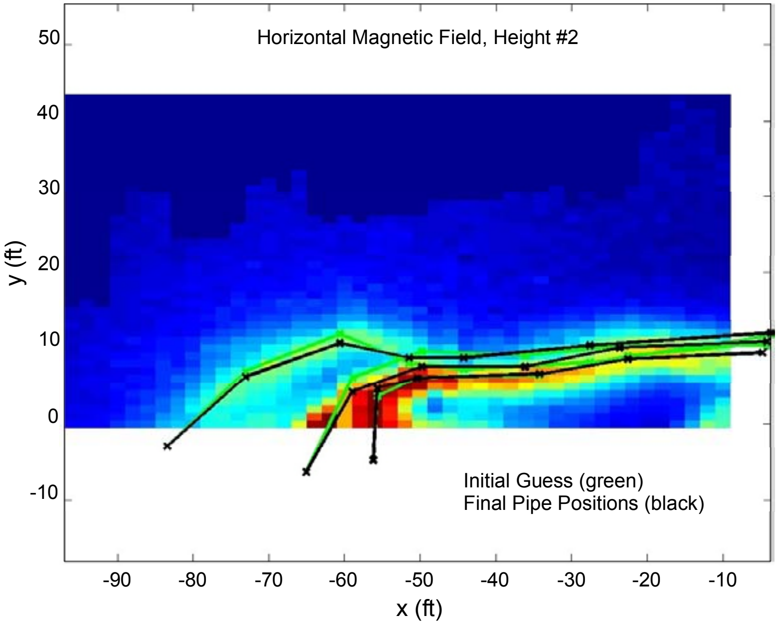


(Top Left) Area surveyed with magnetic field sensors.

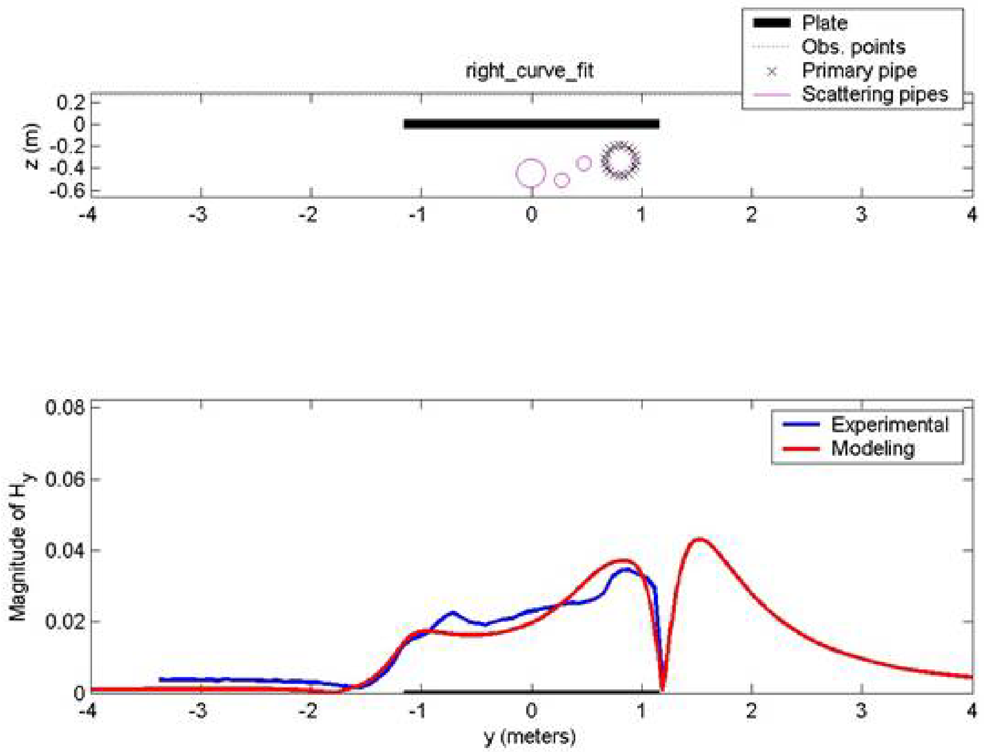
(Middle Left) Clamp-on location and transmitter. The clamp-on location lies outside the surveyed area at (-62 ft, -20 ft).

(Top Right) Magnitude of the horizontal magnetic field at 32 kHz over the survey area.

(Bottom Right) Green lines show initial guess for pipe locations; black lines shows final inverted locations obtained by matching the magnitude field. All final node points lie between one and two feet below the surface



Modeling of plate covered pipes in NYC



The configuration consists of two large pipes carrying high-voltage transmission lines and two smaller pipes carrying dielectric fluid circulated to cool the lines.

The plot below shows the horizontal component of the magnitude field (blue) along a typical profile perpendicular to the lines, as measured when current at 8.2 kHz is injected directly onto one large conduit (one of the galvanic leads is attached to the outside of the pipe at the bottom of the photo; the other lead is grounded through a stake in the soil).

The profile in red is the magnetic field calculated by the parametric model, which takes into account currents flowing along all four conduits (some of the injected current leaks onto the other conduits) and their interaction with a metal plate that covers the conduits.

Summary
and
Outlook for 2004
and beyond

Summary

- Project met all major milestones
  - Built a functional prototype AIR system in the first year!
  - Field tested system
  - Conducted larger scale survey with both arrays
- Project will finish in 2nd year concentrating on:
  - processing, interpretation and improving the data quality
  - adding on-board transmitter

Project plan adjustments

- Based on some project findings in 2003 and results of first larger field test, which are:
  - Need to improve sensors with the help of EMI
  - Need to do more extensive field testing of AIR system with clamp-on transmitters before starting to finalize on-board transmitter design
- Received a contract extension with additional funding from the U.S. DOT to insert 3 months in project schedule at the beginning of 2004

Dual Array System Outlook for 2004

- Improve sensors with help of EMI
- Add on-board transmitter functionality
- Field Testing - Field Testing - Field Testing
  - (looking for more suitable sites and projects)
- Software improvements throughout all software modules (Data acquisition, processing, visualization, modeling and inversion)

… and beyond

- Final results of this project are an experimental prototype (EXP) and the complete system design for an Engineering Prototype (ENP), which is a fully integrated version of the dual array EXP
- Follow-on ENP development would take between 12 and 18 months starting in 2005
  - Estimated cost of ENP development $1.2M
  - Target cost for commercial integrated dual array is $150k

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